中國機械工程學刊第四十三卷第三期第 217~228 頁(民國一百一十一年)
Journal of the Chinese Society of Mechanical Engineers, Vol.43, No.3, pp.217~228 (2022)

On the Study of Ancient Chinese Mechanical Astronomical Clocks

Zheng-Hui Hwang*, Tsung-Yi Lin** and Hong-Sen Yan***

Keywords: Water-powered astronomical clock, design specification, Reconstruction Design, mechanism design,Structural synthesis

ABSTRACT

This paper aims to explore the different systems that made up mechanical astronomical clocks in ancient China by analyzing and comparing historical records, related literature, and reconstruction work conducted by modern scholars. Before the development of the waterwheel steelyard clepsydra, power systems in astronomical clocks were believed to be waterwheels and floats, and the transmission elements likely consisted of ropes and heavy hammers or gear assemblies, which all together synchronized the celestial globe with movements of celestial bodies. With the development of the waterwheel steelyard clepsydra in the 8th century, time-keeping function was added to astronomical clocks, and the transmission system mostly consisted of gear assemblies. As the calendar system and mechanical skills advanced during the Song Dynasty, improvements were made on the waterwheel steelyard clepsydra, and astronomical clocks with multiple time-telling systems and different types of astronomical devices were developed. Influenced by western technology, time-telling mechanisms and astronomical devices used in astronomical clocks during the Yuan Dynasty gradually moved away from the use of waterwheels, and water-powered mechanical clocks were developed.

Paper Received January, 2021. Revised June, 2021. Accepted June, 2021. Correspondence Author: Zheng-Hui Hwang (pmew070010604@gmail.com)

**Ph.D. Candidate, Department of Mechanical Engineering, National Cheng Kung University, Tainan 70101, Taiwan, R.O.C.*

***Professor, Department of Mechanical Engineering, Southern Taiwan University of Science Technology, Tainan 71005, Taiwan, R.O.C.*

**** Chair Professor, Department of Mechanical Engineering, National Cheng Kung University, Tainan 70101, Taiwan, R.O.C.*

INTRODUCTION

In ancient China, emperors through the dynasties believed that changes in astronomical phenomenon were signals from the heavens foretelling misfortunes and fortunes of mankind. For this reason, astronomical observation became an important policy measure for emperors in formulating calendar systems and in consolidating their rule. Astronomical clocks in ancient China were water-powered devices that simulated movements of celestial bodies.

During the Eastern Han Dynasty, the water-transport celestial globe developed by Zhang Heng (78-139 **CE**) was the most typical astronomical clock in ancient China [Wei, 1962; Fang, 1974; Xu, 1972], and dynasties from then on also developed water-powered astronomical clocks. After the 8th century, astronomical clocks with steelyard clepsydra, time-telling mechanism, and two rings that represented the Sun and Moon were developed. During the Song Dynasty (960-1279 **CE**), astronomical clocks with mechanism to depict the motion of celestial bodies, multi-level wooden time-telling pagoda, and multi time-telling system were developed. In the Northern Song Dynasty, the *shui yun yi hsiang tai*, or water-powered armillary sphere and celestial globe tower, developed by Su Sung (1020-1101 **CE**) and Han Gong Lian was regarded as the most versatile astronomical clock in the world before the 14th century. Prior to the Song Dynasty, records of astronomical clocks were brief and simple, which made their contents difficult to understand. Before the 13th century, Arab scientists invented several water-powered mechanical clocks [Hill, 2012]. By the Yuan Dynasty (1271-1386 **CE**), much Arabian technological knowhow was introduced. Prof. Moon-Hyon Nam of Konkuk University believed that the self-striking water clock and the *Heumgyeonggaknu* water-hammering type automatic water clock built by Korean scientist Jang Yeong-Sil (1383-1450 **CE**) of the Joseon Dynasty were heavily influenced by technology of the Yuan Dynasty and the water-powered mechanical clocks designed by the Arabian scientist Al-Jazari (1136-1206 **CE**) [Nam, 1995].

This work aims to explore the history of astronomical clocks in ancient China. By reviewing reconstruction studies conducted by modern scholars and other relevant literature, this study investigates, analyzes, and compares the functions and evolution of ancient astronomical clocks in China.

HISTORICAL DEVELOPMENT

The sections review historical records of ancient astronomical clocks in China, as well as reconstruction studies conducted by modern scholars.

1. Historical Records

In ancient China, the development of astronomical clocks brought about technical evolutions, including astronomical clocks with hydraulic devices, astronomical clocks with time-telling mechanisms, and watered-powered clocks without astronomical instruments.

(1) Astronomical clocks with hydraulic devices

Mechanization of water clocks started with the development of the water-powered astronomical clocks, which were a combination of *lou ke* (clepsydra) and astronomical instruments. The earliest astronomical instrument was a *hun xiang* (celestial globe). The "Volume on Astronomy" in *Chin Shu* by Fang Xuan Ling (648 **CE**) stated: "During the reign of Shun Emperor, Zhang Heng built a *hun xiang*. It had outside and inside rings that rotated. On the surface were carved the north pole and south pole, haung chitao (ecliptic and equinoctial points), 24 solar terms, 28 xing xiu (constellations), zhongwai xingguan, as well as the Sun, Moon and wuwei (five stars). The device rotated using steady dripping water, and was placed in the imperial hall. When the sphere turned, the appearance of the stars coincided with that in the sky. It was a rotating mechanical device that had a date counting mechanism known as *ruilun mingjia*, which raised and lowered a leaf following the waxing and waning of the Moon" [Fang, 1974]. According to the above description, which is the earliest known record on the driving mechanism of a *hun xiang*, Zhang Heng's water-powered *hun xiang* used a clepsydra, power device, *hun xiang* (celestial globe), and *ruilun mingjia* mechanism for its movement. Subsequently, *hun xiangs* developed by Lu Qui (188-219 **CE**), Wang Fan (260 **CE**), and Geng Xun (?-618 **CE**) were believed to have been built based on the work of Zhang Heng.

(2) Astronomical clocks with time-telling mechanisms

These include the water-transport celestial globe built by the Buddhist monk Yi Xing (683-727 **CE**), *the Taiping armillary sphere* (mercury-transport armillary sphere) built by Zhang Si Xun during the Northern Song Dynasty (960-1127 **CE**), the water-powered armillary sphere and celestial globe tower built by Su Sung (1020-1101 **CE**) during the Northern Song Dynasty, and the Lingtai celestial globe built by Guo Shou Jing (1231-1316 **CE**) in the Yuan Dynasty. The main transmission devices included: *lou ke* (clepsydra), power device, *hun xiang* (armillary sphere), and a time-telling mechanism. During this time, the waterwheel steelyard-clepsydra device had also been developed.

(a) Water-transport celestial globe built by the Buddhist monk Yi Xing

Nearly 600 years after Zhang Heng built his water-powered celestial globe, the Buddhist monk Yi Xing, whose secular name was Zhang Sui, and Liang Ling Zhan in 723 also built a water-powered celestial globe. The clock was able not only to demonstrate the movements of the celestial sphere and the Sun and the Moon, it was also able to strike a drum and a bell according to the hour; it was in essence a water-powered astronomical clock. During the Later Jin Dynasty, the "Volume on Astronomy" in *Jiu tang Shu* by Liu Xun (945 **CE**) documented the driving mechanism of the water-powered celestial globe. It was the earliest known description of an autonomous time-telling device, but unfortunately, there was no specific description on the wheel axle, hooks and locks, and their interaction, although for Yi Xing during that time, it was not difficult to integrate the mechanical wooden puppet into the astronomical clock. In addition, there were also astronomical clocks that had two rings representing the Sun and Moon. These included the astronomical clock ji heng built by Wang Fu (1079-1126 **CE**) during the Northern Song Dynasty and the Lingtai celestial globe built by Guo Shou Jing (123-1316 **CE**) in the Yuan Dynasty.

(b) Taiping armillary sphere (mercury-transport armillary sphere) built by Zhang Sixun during the Northern Song Dynasty

Both the "Volume of Astronomy" in the *History of Song* (1343 **CE**) and *Hsin yi hsiang fa yao* (*New Design for an Armillary Sphere and Celestial Globe*) (1094-1096 **CE**) contained descriptions of the driving mechanism of the *Taiping* armillary sphere built by Zhang Si Xun during the Northern Song Dynasty. There were more specific descriptions of the time-telling device, as well as the astronomical instrument used to depict the Sun, Moon, five planets, and *xingguan* [Tuo, 1983; Hu, 1997]. In addition, the time-telling mechanism consisted both sound and visual indicators, which were able to accurately tell the 12 *si chen* (12 double hours within a day), 100 *ke* (100 equal intervals within a day), and *gengdian* (the time at night).

(c) Water-powered armillary sphere and celestial globe tower built by Su Sung during the Northern Sung Dynasty

Following Zhang Si Xun, Su Sung and Han Gong Lian in 1088 built a clock tower, which was an astronomical instrument consisting of an armillary sphere and celestial globe. The design included a time-telling device and water-powered astronomical clock. The time-telling system consisted of a day and night time-keeping wheel and a five-story wooden pagoda. Using image and sound, it was able to present the three methods of time-keeping during that time. The mechanical structure included four types of percussion instruments (a bell, drum, small bell, and gong), four striking wooden puppets with movable arms, and 158 time-reporting wooden puppets wearing specific signs and clothes of different colors (scarlet, purple, and green) [Yan & Lin, 2002]. There was also a multi-cam mechanism that caused the mechanisms at each level of the wooden pagoda to interact, so as to synchronize sounds and display specific signs to indicate time. For instance, if the bell at level one rang, a wooden puppet bearing a sign for the corresponding zheng hour would appear at level two, and another wooden puppet bearing a sign for the corresponding *chu* or *ke* would appear at level three. It was a sophisticated design with great scientific and artistic value [Lin, 2001; Yan, 2007].

(d) Lingtai celestial globe built by Guo Shoujing in the Yuan Dynasty

In 1298, Guo Shou Jing built the *Lingtai* celestial globe, the main function of which was to demonstrate the movement of celestial bodies. Because the sun and moon move at different speeds, and because the ecliptic and the celestial equator do not lie of the same plane, a series of toothed wheels was used to convert speeds and directions. A description of the mechanism used was recorded *Xu Zhizhi tongjian* (*A Sequel to Zhi zhi tong jian*).

(3) Watered-powered clocks without astronomical instruments

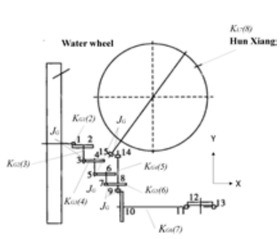
After the Song dynasty, astronomical clocks gradually became independent from astronomical instruments, and its development moved toward the direction of mechanical clocks. For instance, *Da ming dian deng lou* (lantern clepsydra) developed by Guo Shou Jing during the Yuan Dynasty was a hydro-mechanical clock with a mechanism to indicate *si xiang* (four cardinal directions) and a solar and lunar device [Tuo, 1983]; however, there were no records that explained how the clock operated.

2. Reconstruction Studies by Modern Scholars

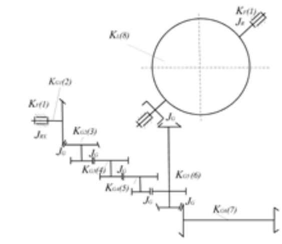
The following is an introduction to reconstruction studies of ancient Chinese astronomical clocks carried out by modern scholars.

(1) Zhang Heng's water-transport celestial globe

Liu Xian Zhou (1890-1975 **CE**), who studied and verified historical records of the celestial globe built by Zhang Heng, reconstructed the celestial globe using a waterwheel as a driving element and a gear mechanism for speed reduction (Fig. 1). To reconstruct the *mingjia* mechanism, Liu used a cam mechanism and designed a mechanism consisting of 15 *ming jia* leaves, using the speed reduction function of the cam mechanism to simulate the withering of a leaf each day [Liu, 1957]. In addition, Chen Kai Ke, in reconstructing the water-transport celestial globe, also used a waterwheel as the driving mechanism to reduce the speed of the cam mechanism in his reconstructed model.



(a) The original illustration of the astronomical device [Liu,1957]

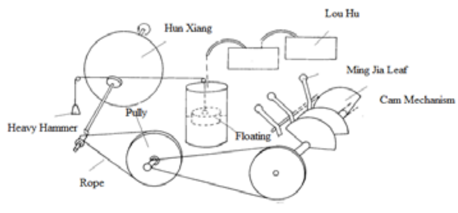


(b) Structural sketch

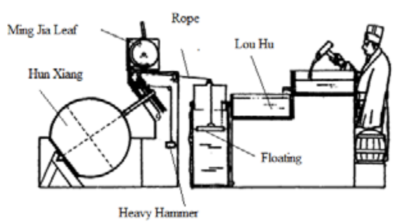
(c) The reconstructed model [Feng, 2019]

Fig. 1. Restoration study of Zhang Heng's water-transport celestial globe, by Liu Xian Zhou

In 1992, Lee Zhi Chao (1935-2020 **CE**) and Chen Yu exhibited at the Suzhou Museum a model of the reconstructed water-transport celestial globe. The model used floats as the power system, along with a *mingjia device* that consisted of rope and pulley [Lee & Chen, 1993], Fig. 2.



(a)Power System [Lee & Chen, 1993]

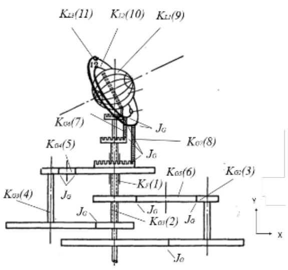


(b)Restoration concept [Lee, 2014]

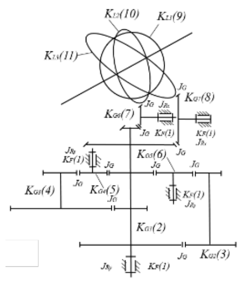
Fig. 2. Zhang Heng's water-transport celestial globe, by Lee Zhi Chao

(2) Yi Xing's water-transport celestial globe

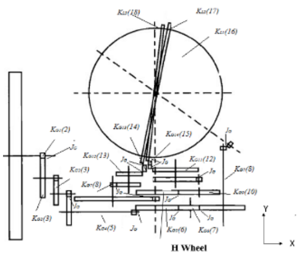
Following his design of the driving mechanism for the celestial globe, Liu Xian Zhou used a five-gear system and a two-cam mechanism to design two separate sets of driving mechanisms for the water-transport celestial globe, as in Figs. 3(a)-(b) [Liu, 1957]. The driving mechanism included a gear system made up of pairs of gears, which enabled the waterwheel to rotate at a constant speed of 1920 revolutions per day. In addition, a set of accelerator gears drove the time-telling mechanism, while another set of speed-reducing gears was used to move the rings that represented the Sun and the Moon.



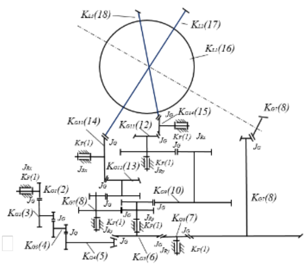
(a) Original illustration I



(b) Structural sketch I



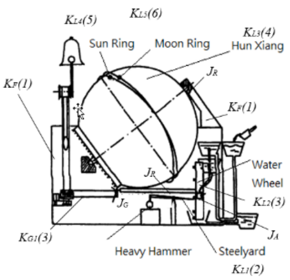
(c) Original illustration II



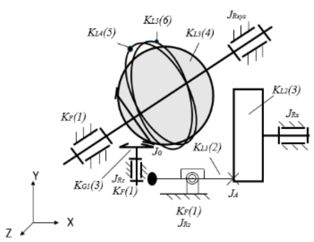
(d) Structural sketch II

Fig. 3. Gear drive system of the water-transport celestial globe, by Liu Xian Zhou [Liu, 1957]

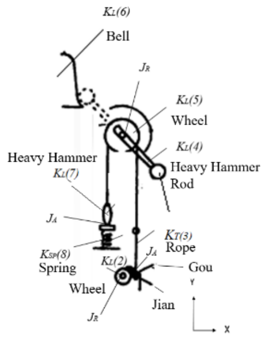
The "Volume on Astronomy" in *Jiu tang Shu* contained the description "the hooks and keys were intertwined and the locks were held together" [Lee, 2014]. Lee Zhi Chao believed that it was used to describe the waterwheel steelyard-clepsydra and the time-telling mechanism of the water-transport celestial globe, Figs.4(a)-(b).



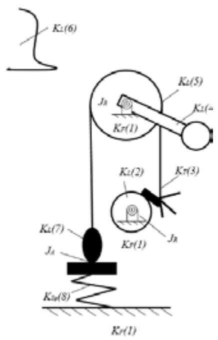
(a)Original illustration



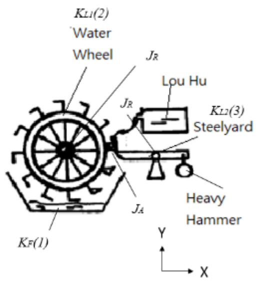
(b)Structural sketch



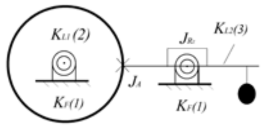
(c) Original illustration of the time-telling mechanism



(d) Structural sketch of the time-telling mechanism



(e) Original illustration of water wheel steelyard-clepsydra device



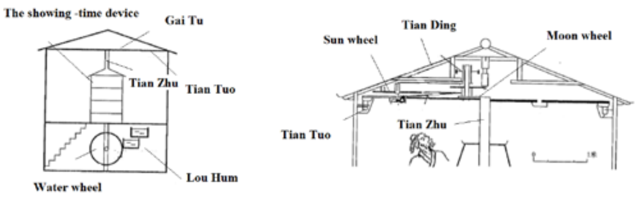
(c)Structural sketch of water wheel steelyard-clepsydra device

Fig. 4. Concept for the reconstruction of the water-transport celestial globe, by Lee Zhi Chao [Chen &Hua,2007]

(3) Zhang Sixun's mercury-transport armillary sphere

According to Li Di (1927–2006 **CE**), the transmission system of the Su Sung's *shui yun yi hsiang tai* (water-powered armillary sphere and celestial globe tower) was designed with reference to the *Taiping armillary sphere* (mercury-transport armillary sphere) built by Zhang Si Xun. At the upper level of *the Taiping armillary sphere* was a *jia tian yi* (artificial sky apparatus), at the middle level was a celestial globe, while at the lower level was a time-telling mechanism and a time-showing mechanism, which consisted of 12 deities each holding a display to tell the time of day [Lee, 1984].

Lee Zhi Chao believed that the mercury-transport armillary sphere had an escapement regulator. The time-telling mechanism was driven by a waterwheel steelyard-clepsydra device, as shown in Fig. 5(a). In addition, there was a *tian zhu* (vertical axle) that drove the mechanism that depicted the motion of celestial bodies, which very likely consisted of an assembly of gears, ropes, and pulleys, Fig. 5(b).

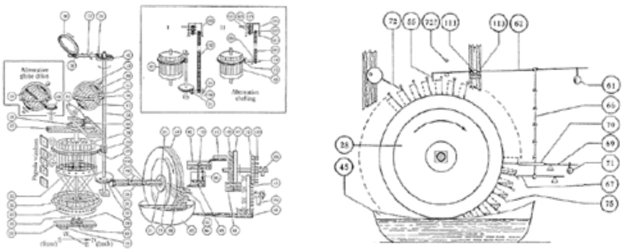


(a) Time-telling and time-showing device (b) Mechanism to depict the motion of mechanism celestial bodies

Fig. 5. Concept for the reconstruction of the mercury-transport armillary sphere, by Lee Zhi Chao [Lee, 2014]

(4) Su Sung's *Shui yun yi hsiang tai*

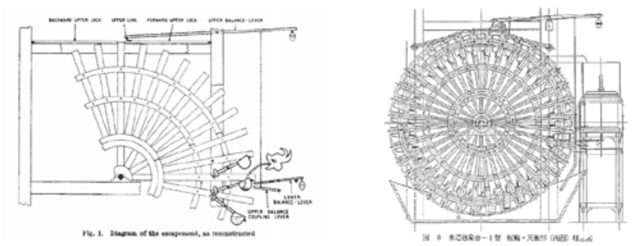
The *Hsin yi hsiang fa yao (New Design for an Armillary Sphere and Celestial Globe)* by Su Sung of the Northern Song Dynasty had four subsequent editions, namely: *Siku Quanshu (1773-1781 **CE**), Shoushan Geshu (1846 **CE**), Wanyou Wenku (1929 **CE**), and Congshu Jicheng Chubian* (1935-1937 **CE**). Modern Chinese and western scholars have referred to these four editions in their efforts to reconstruct the *shui yun yi hsiang tai* (water-transport armillary sphere and celestial globe tower) [Liu, 200; Zheng &Zheng, 2019]. From 1935 to 1954, Liu Xian Zhou determined that the *shui yun yi hsiang tai* used gears and chains to drive the wheel and escapement regulator, which in turn drove the time-telling mechanism and astronomical device [Zheng & Zheng, 2019]. In 1956, Joseph Needham (1900-1995 CE) et al. published an article titled *"Chinese Astronomical Clockwork"* in the *Journal Nature*. This article illustrated the transmission mechanism as well as the driving wheel and waterwheel steelyard clepsydra assembly of the *shui yun yi hsiang tai*, in Fig. 6 [Needham et al, 1956]. The main power of the *shui yun yi hsiang tai* is from the intermittent periodic movement produced by the escapement regulator. However, *Hsin yi hsiang fa yao* did not have detailed description of how the water-receiving scoops were affixed to the driving wheel. Therefore, the research on the fixing method of the water-receiving scoops on the driving wheel has become the key to the successful reconstructions of the *shui yun yi hsiang tai*.



(a)Internal mechanism (b) The driving wheel

Fig. 6. Reconstruction of the *shui yun yi hsiang tai*, by Joseph Needham [Needham et al., 1956]

In 1958, Wang Zhen Duo (1911-1992 **CE**) affixed the water-receiving scoops to the driving wheel, the reconstructed model failed to work. In 1961, J.H. Combridge believed that the water-receiving scoops must have a certain range of rotation on the driving wheel. Therefore, he added a short shaft between the water-receiving scoop and the driving wheel to solve the problem that Wang Zhen Duo's driving wheel could not rotate[Combridge,1964], Fig. 7(a). In 1988, Chen Yan Hang and others constructed a 1:8 scale model using rotating water-receiving scoops, and the model is on display at the Su Sung Science and Technology Museum [Zheng &Zheng, 2019]. In 1997, the Japanese engineer Hideo Tsuchiya modified the structural appearance of upper stopping device, [Hideo, 1993; Zheng &Zheng, 2019], thereby solving the problem of the driving wheel overturning, Fig. 7(b). In 2001, Tsung-Yi Lin summarized the design specifications of the Su Sung's escapement regulator and studied the scientific and technological level of the Northern Song Dynasty, based on the systematic reconstruction procedure developed by the methodology of creative mechanism design, and taking into account the principles of mechanical evolution and mutation, 10 sets of feasible reconstruction design models of the Su Sung's escapement regulator were available, and he chooses a set of reconstruction design models and makes the physical model,Fig7.(c) [Yan, 2007]. In addition, Tsung-Yi Lin also added a water lifting device to his reconstruction work for Su Sung's escapement regulator, Fig7. (d). Because of the successful improvement of Su Sung's escapement regulator, modern scholars are actively reconstructing the *shui yun yi hsiang tai*, and many of reconstruction models with different proportions being also manufactured in the same time.



(a) John Cambridge [Combridge, 1964] (b) Hideo Tsuchiya [Hideo,1993]

(c) Tsung-yi Lin [Yan,2007] (d) Tsung-yi Lin [Yan, 2007]

Fig. 7. Reconstruction of Su Sung's escapement regulator

(5) Guo Shoujing's Da Ming Dian Deng Lou

Lee Zhichao and Chen Kaige separately reconstructed Guo Shou Jing's *Da Ming Dian Deng Lou* (lantern clepsydra), using the waterwheel as the power mechanism while referring to historical records for the reconstruction of other mechanisms.

FUNCTIONAL SYSTEMS

The components of an astronomical clock include a *Lou ke* (water clock), a power system, a control system, a transmission system, a time-telling and time-showing mechanism, and an astronomical device. In addition, Su Sung's water-powered armillary sphere and celestial globe tower also included a water lifting mechanism that used a manually-operated waterwheel. Historical records of water-powered astronomical clocks in ancient China were short and simple, and there were limited descriptions on how the *Lou ke* drove the celestial globe and how the time-telling device operated and was activated. The following is an analysis of the different components of ancient Chinese astronomical clocks.

1.The lou ke System

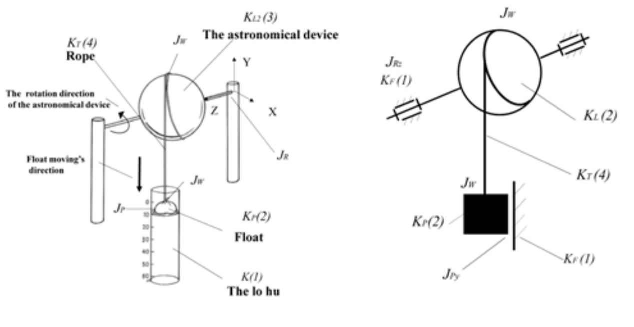
In order to improve the accuracy of timekeeping, water clocks evolved from single-vessel outflowing clepsydra (156-87 **BCE**) to single-vessel inflowing clepsydra (156-87 **BCE**), two-level compensating floating-arrow clepsydra (78-139 **CE**) three-level compensating floating-arrow clepsydra (317V420 **CE**), four-level compensating floating-arrow clepsydra (655 **CE**), and inflow clepsydra with overflow tank (1030 **CE**) [Lin, 2001]. The ancient Chinese records clearly showed that Zhang Heng's water-transport celestial globe and Su Sung's water-powered armillary sphere and celestial globe tower were two-level compensating floating-arrow clepsydras; however, there was a lack of detailed records on the other astronomical clocks. In addition, the Daoist monk Li Lan invented the *chenglou* (steelyard clepsydra) during the Northern Wei Dynasty (386-534 **CE**) [Xu, 1972]. *Hsin yi hsiang fa yao* contained an illustration of the escapement regulator used in Su Sung's water-powered armillary sphere and celestial globe tower. It consisted of a time-keeping *cheng lou* device, which used a waterwheel to create periodic movements.

2.The Power System

There were two power systems used in water-powered mechanical clocks: one that used a system of floats and one that used a waterwheel. The power systems are explained below.

(1) Power systems using floats

During the 5th century, the Indian astronomer Āryabhaṭa (476-550 **CE**) used floats as a driving device to rotate wooden celestial globes, Fig. 8 (Sarna,2018).



(a)Original illustration (b) Structural sketch [Hwang et al.,2021]

Fig. 8. Aryabhata's power system that used floats as a driving device [Sarma, 2018]

Arab scientists during the medieval times used floats, ropes, and hammers as power systems to drive water-powered mechanical clocks. Before the 8th century, the history of ancient Chinese astronomical clocks did not contain records of power systems. Because floating arrow clepsydras appeared after Emperor Wu of Han (156-87 **BCE**) [Lin, 2001], it can be inferred that floats were used during the Western Han Dynasty (202 **BCE**-9 **CE**). Therefore, it is highly likely that ancient Chinese astronomical clocks used floats as their power system to synchronize astronomical devices with the movements of celestial bodies.

(2) Waterwheel power systems

The *shui dui*, or watermill, is the most ancient waterwheel machinery in China [Lu & Hua, 2000]. Although the vertical waterwheel had been developed by the Eastern Jin Dynasty (317-420 **CE**), it was not until the 8th century that there were records indicating that waterwheels were used as power systems in astronomical clocks. Lu Jing yan and Hua Jue ming believed that the power drive system of the water-transport celestial globe built by the Buddhist monk Yi Xing and Liang Ling Zhan was a vertical waterwheel [Lu & Hua, 2000]. In the 11th century, *Hsin yi hsiang fa yao* contained detailed illustrations that showed the waterwheel mechanism of the water-transport celestial globe consisted of a pilot wheel assembly.

3.The Control System

The control system was used to help the power transmission system drive the astronomical transmission mechanism, so that the astronomical device of the astronomical clock could be synchronized with movements of celestial bodies. The following is a description of control systems that used floats and waterwheels as their driving elements.

(1) Floats

The Book of Knowledge of Ingenious Mechanical Devices by Al-Jazari contained a description of an elephant water clock and a mechanism that controlled a float to trigger a cyclic series of movements. The mechanism consisted of two mechanical snakes and a bowl floating in water. When the bowl sank to a specified level, it released a mechanism that would drop a ball into the mouth of a serpent, which sent the ball to the time-telling mechanism and triggered it in the process. Thereafter, the double-snake mechanism would return to its initial position and a string would pull the bowl back to the surface of the water. The cycle would then repeat itself, Fig. 9 [Hill, 2012].

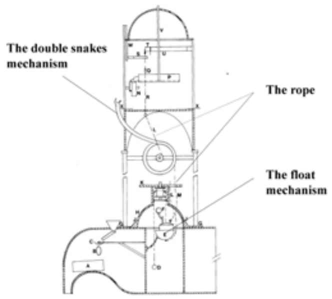
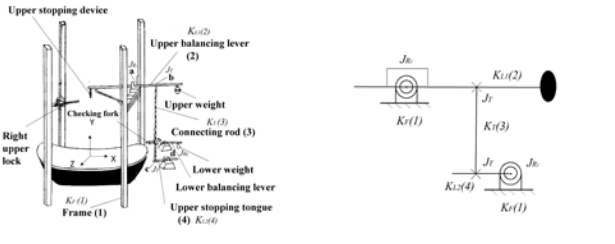


Fig. 9. Float mechanism and double-snake mechanism of Al-Jazari's Elephant Water Clock [Hill, 2012]

If ancient Chinese astronomical clocks were driven by floats, there must be a control mechanism so that rotation of the celestial globe would not be disrupted when the floats rose from the bottom to the top of the water vessel [Lee, 2014].

(2) Waterwheels

If the water-powered astronomical clock used waterwheel as its power transmission element, the escapement regulator mechanism must be the waterwheel control mechanism, so as to allow the waterwheel to produce periodic, intermittent movements. *Hsin yi hsiang fa yao* contained texts and illustrations of the *tian heng mechanism* (upper balancing lever) of the *shui yun yi hsiang tai*. The entire mechanism consisted of the *tian heng* (upper balancing lever), *tian chuan* (upper weight), *shu heng* (lower balancing lever), *shu quan* (lower weight), *guan she* (upper stopping tongue), *ge cha* (checking fork), and the left and right *tian shuo* (left, right upper lock), Fig.10 [Hu, 1997].



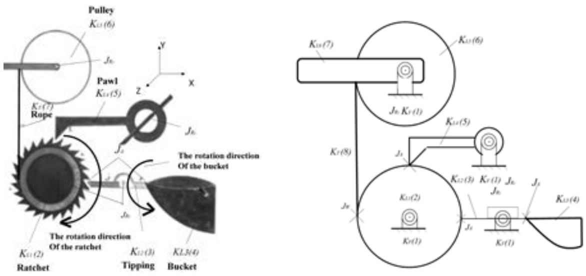
(a) Original illustration[Hu,1997] (b)Structural sketch[Yan &Hsiao, 2014]

Fig. 10. *Tianheng* (upper balancing lever)

As shown in Fig. 10, the *tian heng* mechanism consisted of a connecting rod and a lever mechanism; water from the receiving vessel forced the checking fork to pull on the left upper lock and upper stopping device to control the motion of the driving wheel. However, the waterwheel steelyard-clepsydra of the *shui yun yi hsiang tai* was not the first of its kind. In "Luli Zhi" and "Volume of Astronomy," both from the *History of Song*, there contained a passage that read: "since I understood the mechanism from Yi Xing of the Tang Dynasty" and a description of *kai yuan yi fa*, which was the method Yi Xing used to build his water-transport celestial globe [Song, 1976]. The two passages described the operating principles of the waterwheel steelyard-clepsydras of Wang Fu (1079-1126 **CE**) and Zhang Si Zun of the Northern Song Dynasty, and mentioned that it was very likely that the mechanisms were patterned after that of Yi Xing.

On Yi Xing's waterwheel steelyard-clepsydra device, the "Volume on Astronomy" in Jiu tang shu (945 **CE**) stated in Chinese: "*gou jian jio cuo, guan suo xiang ch*i," which literally translated to: The hooks and keys are intertwined, and the locks are held together [Liu, 1976]. The Chinese character *guan* (關) refers to a mechanism that could open and close, the character *suo* (鎖) refers to a lock, while *xiang chi* (相持) means "firmly opposed and will not give way to each other" [Xu, 1963]. Therefore, it can be inferred that Yi Xing's mechanism consisted of a waterwheel, a device that was able to open and close, a lock mechanism, and another device that could toggle on and off while simultaneously triggering the lock.

In addition, the peacock clock as described in Al-Jazari's *The Book of Knowledge of Ingenious Mechanical Devices*, consisted of a ratchet mechanism that was able to keep time and a mechanism that was controlled on an hourly basis to tell and display time. Its function was similar to the waterwheel steelyard-clepsydra device in ancient China, Fig. 11.



(a) Original illustration [Hill, 2012] (b) Structural sketch[Hwang et al.,2021]

Fig. 11. Al-Jazari's ratchet mechanism

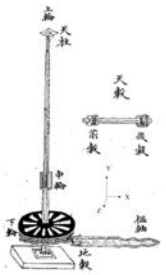
The *"Volume on Astronomy"* in *Yuan Shi* (*The History of Yuan*) (1370 **CE**) did not contain detailed description of the power transmission system used in the *Da ming dian denglou* (lantern clepsydra) built by Guo Shou Jing. If a waterwheel was used as the driving mechanism, it is likely that Guo Shou Jing patterned his waterwheel steelyard-clepsydra device after previous designs, and it is also likely that Guo referred to the waterwheel control systems of water-powered mechanical clocks of Arab scientists.

4.The Transmission System

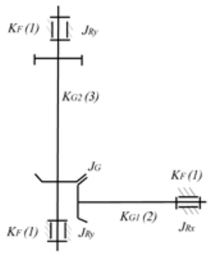
Transmission systems in ancient Chinese astronomical clocks were dependent on the power system used. If floats were used as a power system, the transmission mostly consisted of a system of ropes, hammers, and pulleys. The ancient Greek mathematician Heron of Alexandria (10-70 **CE**) used a transmission system consisting of floats, hammers, and ropes to drive his gear systems [Woodcroft, 2009]. Thus, a mechanical transmission system consisting of floats, hammers, ropes, and pulleys could also be used to drive astronomical clocks with wheel mechanisms.

Hsin yi hsiang fa yao recorded two types of transmission systems used in the *shui yun yi hsiang tai*. One was a gear transmission system, also known as the *tian zhu* mechanism. The second was a hybrid transmission system of sprocket and gear, also known as the *tian ti* mechanism. From this, it can be seen that gear transmission systems were also used in astronomical clocks powered by waterwheels.

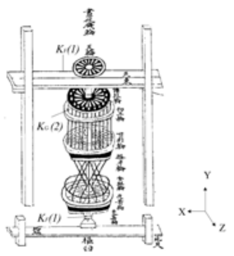
The *tian zhu* mechanism used in the *shui yun yi hsiang tai* moved the astronomical instruments and drove the time-telling and showing mechanism. Fig. 12(a)- (d) show the *tian zhu* mechanism and the day and night time-telling and showing mechanism.



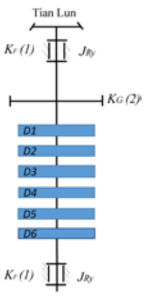
(a)Original illustration of *tian zhu*[Hu,1997]



(b)Structural sketch *of tian zhu*



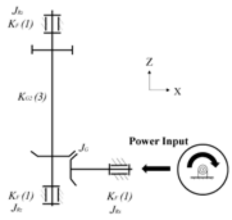
(c)Original illustration of time-telling and showing device [Hu,1997]



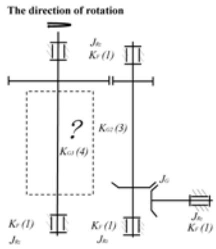
(d)Structural sketch of time-telling and showing device [Hwang et al., 2021]

Fig. 12. Day and night time-telling and showing mechanism used in the *shui yun yi hsiang tai*

Reviewing the *tian zhu* mechanism and the time-telling and showing mechanism in Fig. 12 and examining the historical records of the *Taiping* armillary sphere, it is thus possible to deduce the *tian zhu* mechanism and the time-telling and showing mechanism of *the Taiping armillary sphere*. Fig. 13 (a) and (b).



(a)Transmission system



(b) Time-reporting and showing device

Fig. 13. Transmission system of *the Taiping armillary sphere*

Although it is clear what the components of the transmission system used in *the Taiping armillary sphere* were, the number of rods used in the time-telling and showing mechanism, as well as the transmission system used, remains unclear. It can only be inferred that the astronomical clock had a transmission system for the mechanism that showed movements of the celestial bodies, as well as a single mechanism for time-telling and showing.

5.The Time-telling and Time-showing System

In ancient China, records of time-telling mechanisms in astronomical clocks started to appear after the 8th century. These mechanisms were mostly designed to accommodate the *shi chu* (initial hour), *shi zheng* (central hour), *da ke* (major *ke*), *xiao ke* (minor *ke*), and *geng* (time during the night) within each *si chen*. In addition, there were also time-telling mechanism that used either wooden puppets or copper balls. During the Northern Song Dynasty, Zhang Si Xun developed his *Taiping* armillary sphere using wooden puppets that showed the 12 *si chen* within a day. The two time-telling mechanisms are explained below.

(1) Time-telling mechanism using wooden puppets

The wooden puppet time-telling mechanism was an application of the cam mechanism. Ma Jun of the Three Kingdoms (220-226 **CE**) developed a mechanical toy that used a waterwheel and a *shui dui*, or watermill, to drive wooden puppets. Joseph Needham believed that the wooden puppet time-telling mechanism in the water-transport celestial globe built by the Buddhist monk Yi Xing and Liang Ling Zhan was based on Ma Jun's waterwheel mechanism [Needham, 1965]. There were two types of time-telling mechanisms, one with drums striking at every *ke*, and the other with bells striking at every *si chen*. After the Song Dynasty, a mechanism that would shake bells to tell time and a mechanism that would strike a *zheng* (a small gong) during nighttime were also developed.

In ancient China, the *bai ke zhi* system of measuring time divided a day into *ke* (100 equal units), while the *shi chen* system divided a day into *chen* (12 dual hours).

Because 100 is indivisible by 12, in the Tang Dynasty Yi Xing divided one *chen* into five *ke*, which resulted in 60 *ke* in one day. This process overcame the incompatibility between the *bai ke zhi* system and *shi chen* system of time-telling [Cao, 1986]. Thereafter, time-telling mechanisms and waterwheel escapement mechanisms were developed. After the Song Dynasty, a *shi chen* was divided into eight and one-third *ke*, and the one-third *ke* was referred to as *xiao ke* (minor *ke*). The "Volume of Astronomy" in the *History of Song* described the *Taiping* armillary sphere built by Zhang Si Xun as having a time-telling mechanism with "seven deities on duty" and a time-showing mechanism consisting of 12 deities each holding a display to tell the time of day. From this, it can be seen that both the *bai ke zhi* and *shi chen* system of measuring time had become integrated into the time-telling and showing mechanisms of astronomical clocks. This mechanism was developed in more detail in Su Sung's *shui yun yi hsiang tai*, Fig. 14 [Hu, 1997].

(a)Time-keeping wheel for reporting time of day (b) Time-keeping wheel for reporting shi chu and shi zheng (c) Time-keeping wheel for reporting *ke*

Fig. 14. Time-telling and showing mechanism of the *shui yun yi hsiang tai* [Hu, 1997]

In chronological order, astronomical clocks that had a time-showing mechanism consisting of 12 deities included: *the Taiping armillary sphere* built by Zhang Si Xun during the Northern Song Dynasty (960-1127 **CE**), the Lingtai celestial globe built by Guo Shou Jing (1231-1316 **CE**), the self-striking water clock and *Heumgyeonggaknu* water-hammering type automatic water clock developed by the Korean scientist Jang Yeong-Sil (1383-1450 **CE**). Among them, the time-showing mechanism of the *Heumgyeonggaknu* water clock used a cam mechanism [Kim et al., 2013].

(2) Time-telling mechanism using copper balls

The use of copper balls to initiate time-telling was first reported in volume 198 of *Jiu Tang Shu* (The Old book of Tang) [Liu, 1976], and this kind of system was very common in water-powered mechanical clocks during the Song Dynasty [Hua, 1991]. In addition, "Volume on Astronomy" in *Yuan Shi* (The History of Yuan) recorded the following: "The second level consisted of statues of a dragon, tiger, turtle, and elephant, each occupying a corner. They leap on designated hours, *nao ming* can be heard from within." In this passage, the phrase *nao ming* likely referred to the sound of copper ball striking the time-telling mechanism in the *Da ming dian deng lou* (lantern clepsydra). This method of time telling was also most widely used among ancient Arab scientists. The self-striking water clock developed by the Korean scientist Jang Yeong-Sil also used the same method to initiate time-telling.

6.The Astronomical Device

In ancient China, the *hun xiang* (celestial globe) was a major component in astronomical clocks, but Su Sung's *shui yun yi hsiang tai* had both a *hun xiang* and a *hun yi* (armillary sphere) at the same time. The *hun xiang* was used to show the movements of celestial bodies, while the *hun yi* was used to measure the coordinate system of celestial bodies, as well as the coordinates and angular distance between celestial bodies [Pan, 2005]. An explanation of the ancient *hun yi* and *hun xiang* follows.

(1) Hun yi (armillary sphere)

The first *hun yi* (armillary sphere) ever recorded in ancient China was the bronze armillary sphere built by Kong Ting during the Former Zhao Dynasty (319-351 **CE**) [Pan, 2005]. During the Tang Dynasty, Li Chun Feng (602-670 **CE**) built an armillary sphere with three rings, the *liu he yi*, *san chen yi*, and *si you yi*, as opposed to the traditional two rings. Because of Li Chun Feng's armillary sphere, subsequent armillary spheres in ancient China included a lunar orbit. The "Volume on Astronomy" in *Jiu tang shu* recorded the dimensions of the *huang dao you yi* built by Yi Xing and Liang Ling Zhan [Liu, 1976; Lee, 1993]. In addition, *Hsin yi hsiang fa yao* contained detailed illustrations of the armillary sphere used in *shui yun yi hsiang tai*.

(2) Hun xiang (celestial globe)

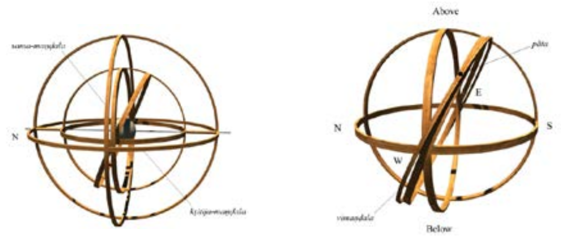
The most reliable historical record showed that *hun xiang* (celestial globe) in ancient China was invented by Zhang Heng in the Eastern Han Dynasty [Fang, 1974]. Before the 11th century, there were no historical records that described the physical appearance of a *hun xiang*. There were several types of ancient Chinese *hun xiang*: one that looked like a modern-day celestial globe, one with revolving heaven and stationary earth, one with two rings that represented the Sun and Moon, and one that showed motion of celestial bodies. They are explained below.

(a) Hun xiang that looked like a modern-day celestial globe

Su Sung's *Hsin yi hsiang fa yao* contained illustrations and texts describing a *hun xiang* and the transmission system of the *shui yun yi hsiang tai*. Most *hun xiang* developed after the Northern Song Dynasty were similar to the type described by Su Sung.

(b) Hun xiang with revolving heaven and stationary earth

In ancient India, *hun yi* (armillary spheres) were used to display the movement of celestial bodies, solve spherical trigonometric problems, and calculate the arrival of a solar eclipse [Lu, 2015]. However, it was only until the 7th century that there were volumes of records in Sanskrit about armillary spheres. The armillary sphere built by Bhāskara I (600-680 **CE**) had a globe in its center, as shown in Fig. 15(a). The construction of the armillary sphere was very similar to those built by Ge Heng during the Period of the Three Kingdoms [Wei, 1962], Qian Lezhi in the Liu Song Dynasty [Fang, 1974], Tao Hong Jing in the Liang Dynasty [Lee, 1976], and Geng Xun in the Sui Dynsty [Wei, 1962]. In addition, the armillary sphere built by Bhāskara I also had an ecliptic and Sun-Moon rings, Fig. 15(b).



(a)The armillary sphere had a globe in its center (b) The ecliptic and Sun-Moon rings

Fig. 15. Reconstruction of the Bhāskara I armillary sphere [Lu, 2015]

(c) Hun xiang that showed motion of celestial bodies

These mechanisms originated from astronomical observatories in the Northern Wei Dynasty. The geographer Li Dao Yuan (472-527 **CE**) recorded their physical appearance in the *Shui jing zhu* (*Commentary on the Water Classic*). In 527, Emperor Wu of Liang (464-549 **CE**) of the Southern Dynasty built *gai tian yi* (hemispherical dome), which covered the ground like a huge umbrella. The dome-shaped heavens covered the earth, while the earth rotated around the polar axis [Pan, 2005]. Zhang Si Xun's *hun xiang* was most likely to be one that showed motion of celestial bodies, which functioned similarly to the *Gai tian yi*.

CONCLUSION

The float is likely the earliest transmission element used in hydraulic machinery and the main transmission element in water-powered mechanical clocks in the ancient West. Evidence of this was provided by the Indian mathematician Āryabhaṭa (476-550 **CE**), who used ropes and floats to cause a wooden celestial globe to rotate. Floats could also likely be the driving element of the astronomical clock developed by Zhang Heng prior to the 8th century. Therefore, the transmission elements of ancient Chinese astronomical clocks were very likely to be floats and waterwheels, with the entire transmission mechanism made up of either rope, pulley, and hammer assemblies or gear assemblies.

After the 8th century, ancient China began to develop waterwheel astronomical clocks with time-keeping functions. The clocks consisted of a waterwheel and steelyard clepsydra, which controlled the movement of the driving wheel, giving it a periodic, start-stop motion. This was also one of the features of escapement regulators in ancient China. Escapement regulators used in astronomical clocks likely consisted of gear assemblies. After the 13th century, the ancient West developed a ratchet mechanism with time-keeping function. While similar in function to that of the Chinese waterwheel steelyard clepsydra, the mechanism instead used ropes and pulleys for transmission. In addition, as the need for a more accurate calendar system increased with each successive dynasty, celestial globes with Sun-Moon rings, as well as astronomical clocks that showed motion of celestial bodies were developed, which led to the development of astronomical clocks with time-telling mechanisms and multiple time-telling systems. Among them, Su Sung's *shui yun yi hsiang tai* was an astronomical clock that integrated multiple ancient Chinese mechanisms, including time-keeping mechanisms, time-telling mechanisms, time-showing mechanisms, mechanisms to show the movement of celestial bodies, mechanisms for astronomical observations. The clock was the culmination of the development of astronomical clocks in ancient China.

The Yuan Dynasty had close interactions with the then Korean dynasty and the Arabs, and much of the science and technology of western Asia were introduced to ancient China during this period. Historical records of the *gong lou* (palace clepsydra) built during the reign of Emperor Shun during the Yuan Dynasty (1320-1370 **CE**) showed that names of internal elements of the clepsydra included many westernized names. Thereafter, the self-striking water clock and *Heumgyeonggaknu* water-hammering type automatic water clock built by Jang Yeong-Sil, the *Da ming dian deng lou* (lantern clepsydra) by Guo Shou Jing, and the *gong lou* (palace clepsydra) of Emperor Shun all used the same names for their mechanisms. It can thus be seen that astronomical clocks during the Yuan Dynasty were new types of water-powered mechanical clocks that that integrated technologies from the East and West.

ACKNOWLEDGEMENT

The authors are grateful to the Ministry of Science and Technology (TAIWAN, ROC) for the financial support of this work.(Grant no. MOST 106-2221-E-006-100-MY3)

REFERENCES

Cao, M., *Zhong Hua Tian Wen Xue Shi* (in Chinese), The Commercial Press Taiwan, Taipei, (1986).

Chen, M.T. and Hua, T.X., *Zhongguo Zi Shi Yi Qi Tong Shi* (in Chinese), Anhui Jiaoyu Chubanshe, Anhui, (2007).

Fang, X. L. (Tang Dynasty), *Jin Shu* (in Chinese), Zhong Hua Book Company, Anhui, (1974).

Feng, L.S., *Reconstructed Photos of Zhang Heng's Hydraulic Astronomical Instrument*, China Science Daily, 4th Edition Characters, (2019.9.27).

Hwang, Z.H et al., "Historical development of Water-

Powered Mechanical Clocks," Mech.Sci, Vo1.12, pp.203-219 (2021).

Heideo, T., "The Reconstruction for the Water-Powered Armillary Sphere and Celestial Globe Tower," *The Horological institute of Japan*, No.145, pp.56-70 (1993).

Hill, P., *The Book of Knowledge of Ingenious Mechanical Devices* (Kitāb fī ma'rifat al-ḥiyal al-handasiyya), Springer Science & Business Media, Berlin, (2012).

Hsiao, K.H. and Yan, H.S, *Mechanism in Ancient Chinese Books with Illustrations*, Dong Hua Books, Taipei, (2014).

Hua, T., *Zhon Gguo Lou Ke* (in Chinese), Anhui Science and Technology Press, Anhui, 1991.

Hu, W.J., *Hsin yi hsiang fa yao: A Modern Interpretation* (in Chinese), Liaoning Jiaoyu Chubanshe, Shenyang, (1997).

Kim, S.H., Lee, Y.-S. and Ham, S.Y., "A Study on the Internal Structure of Heumgyeonggaknu," *Journal of Astronomy and Space Sciences*, Vol.30, No.2, pp.113-121 (2013).

Lee, D., "," *Inner Mongolia Normal University News (Natural Science Edition)*, No.2, pp.50-57 (1984).

Lee, Z.C., "Textual Researches on the Two Armillary Made in the Tang and Song Dynasties," *Studies in the History of Natural Science*, Vol.6, No.1, pp. 120-127 (1993).

Lee, Z.C., *Zhong Guo Shui Zhong Shi* (in Chinese), Anhui Jiaoyu Chubanshe, Anhui, (2014).

Lee, Z.C. and Chen, Y., "A Textual Research and New Reconstruction of Zhang Heng's Water-Rotating Globe," *Studies in the History of Natural Science*, Vol.12, No.2, pp.120-127(1993).

Lee, Y.S. (Tang Dynasty), *Nan Shi·Tao Hong Jing Chuan* (in Chinese), Ding Wen Publishing House, Taipei, 1976.

Lin, T.Y., *A Systematic Reconstruction Design of Ancient Chinese Escapement Regulators*, Ph.D. dissertation, Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan, (2001).

Liu, Q., "Research on the Ancient Documents of the Astronomical Clock Tower of Song Dynasty," *Institute for History of Science and Technology & Ancients*, (2002).

Liu, X., et al. (Later Jin Dynasty), *Jiu Tang Shu* (in Chinese), Ding Wen Publishing House, Taipei, (1976).

Liu, X.Z., "On the Invention of Time-Keeping Apparatus," *Journal of Tsinghua University Science and Technology*, Vol.3, No.2, (1957).

Lu, J.Y. and Hua, J.M., *Zhong Guo Kexue Jishu Shi (Jixie Juan)* (in Chinese), Science and Technology Press, Beijing, (2000).

Lu, P., "Bhāskara I on the Construction of the Armillary Sphere," *History of Science in South Asia*; Vol.3, pp.1-19 (2015).

Nam, M.H., "A Survey Technical on the Astronomical and Timekeeping Instrument during the King Sejong's Reign," *Studies in the History of Natural Science*, Vol.14, No.1, pp.42-50 (1995).

Needham, J., "Chinese Astronomical Clockwork," *Nature*, Vol.177, No.4905, pp.600-602 (1956).

Combridge, J. H.," The Chinese Water-Balance Escapement,"*Nature*,Vol.204, pp.1175-1177 (1964).

Pan, N., *(Cai tu ben) Zhong Guo Gu Tiqn Wen Yiqi Shi* (in Chinese), Shanxi Education Press, Taiyuan, (2005).

Sarma, S.R., "Water clock and Steelyard in the Jyotiskarandaka," *International of Journal of Jaina Studies*, Vol.14, No.2, pp.1-49 (2018).

Song, L. (Ming Dynasty), *Yuan Shi* (in Chinese), Zhong Hua Book Company, Beijing, (1976).

Tuo, T., et al. (Yuan Dynasty), *Song Shi* (in Chinese), Ding Wen Publishing House, Taipei, (1983).

Wei, Z., et al. (Tang Dynasty), *Sui Shu* (in Chinese), Zhong Hua Book Company, Beijing, (1962).

Woodcroft, B., *The Pneumatics of Hero of Alexandria*, Createspace Independent Publishing Platform, California, (2009).

Xu, J., et al. (Tang Dynasty), *Chuxue Ji* (in Chinese), Ding Wen Publishing House, Taipei, (1972).

Xu, S. (Eastern Han Dynasty), *Shuo Wen Jie Zi* (in Chinese), Zhong Hua Book Company, Beijing, (1963).

Yan, H. S, *Reconstruction Designs of Lost Ancient Chinese Machinery*, Springer Science & Business Media, Netherlands, (2007).

Yan, H.S. and Lin, T.Y., "A Study on Ancient Chinese Time Laws and the Time-Telling System of Su Song's Clock Tower," *Mechanism and Machine Theory*, Vol.37, pp.15-33(2002).

Zheng, B. and Zheng, J., "A Review of the Reconstruction of the Astronomical Clock-Tower," *Journal of Dialectics of Nature*, Vol.41, No.4, pp.43-51 (2019).

古中國天文鐘的研究

黃正輝　顏鴻森

國立成功大學機械工程學系

林聰益

私立南台科技大學機械工程系

摘要

本文旨在研究古中國機械天文鐘的組成系統。藉由天文鐘的歷史記載、相關文獻、及近代學者的復原工作，進行綜合性的分析與比較。在尚未發展水輪秤漏裝置之前,天文鐘的動力驅動元件應為水輪與浮子，

傳動元件應為繩索與重錘，或齒輪所組成的傳動系統，帶動渾象模擬與天同步。8 世紀發明水輪秤漏裝置，使得水輪具有計時功能，天文鐘的傳動系統則以齒輪系為主。宋朝時，在曆法、機械工藝技術的發展下，改良了水輪秤漏裝置，亦發展出多元報顯系統、多形式天文裝置的天文鐘。元朝受到西方科技影響，其天文鐘報顯時裝置及天文裝置，逐漸脫離古中國傳統水力機械鐘的模式，發展出新型式的水力機械鐘。